SOFT HADRONIC PHYSICS AT RHIC

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Abstract

Although soft hadronic observables do not probe the early stages of a nucleus-nucleus collision directly, the data can be used to constrain the evolutionary path of the system. I review some of the experimental data from the first year of RHIC operations with Au+Au at $\sqrt{s}_{NN} = 130$ GeV. This data includes particle yields, momentum spectra, and two-particle correlations. The data point to a system that develops strong radial flow and expands to roughly twice the size of the initial system before kinetic freeze-out. The data also suggest a multi-stage freeze-out, where the particle abundances are fixed at an earlier time compared to the end of elastic interactions.

1 Introduction

The Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National laboratory began operations in year 2000 with Au+Au collisions at $\sqrt{s}_{NN} = 130$ GeV. This represents nearly a factor of 8 increase in the available center-of-mass energy compared to experiments at the CERN SPS. It is hoped that by going to higher collision energies, the manifestations of an early partonic phase become more distinguishable experimentally. While some evidence points to the formation of a Quark-Gluon plasma state already at SPS energies, such a state should be longer lived and larger at RHIC energies. Hopefully the partonic state is sufficiently large and long-lived such that the bulk thermodynamic properties of the Quark-Gluon plasma can be explored experimentally.

The large majority of particles produced in such collisions are hadrons. Due to the strength of the strong interaction, these particles cannot escape from the initial partonic stage without undergoing additional re-scattering. Nonetheless, by mapping the full momentum and configuration space distributions of the produced hadrons we hope to gather information about the initial entropy production, early equation of state, and nature of any subsequent phase transition (i.e. first-order versus crossover).

Four experiments at RHIC have published data on the production and/or ratios of soft hadrons. STAR and Phenix are two large experiments that measure hadrons in a large phase-space. Phobos and Brahms are smaller experiments, but have unique capabilities. Here I will present data from these experiments on soft ($p_T < 2$ GeV/c) particle production and correlations among produced particles.

2 Baryon stopping and chemical freeze-out

By going to higher energy nucleus-nucleus collisions we hope to achieve a system with zero net-baryon density in the mid-rapidity region. Under these conditions, we can directly compare to theoretical calculations from lattice QCD. In addition, the primordial QGP to hadron phase transition 10^{-6} seconds after the Big Bang occurred in a nearly net-baryon free region.

All RHIC experiments have measure the $\bar{p}/p$ ratio at mid-rapidity [1, 2, 3]. In Figure 1, the Brahms mid-rapidity results are shown, as well as measurements at slightly larger rapidity [3]. At mid-rapidity, the $\bar{p}/p$ ratio is 0.6-0.7, indicating that RHIC collisions are not at sufficient energy to reach the net-baryon free limit. These values indicate that roughly 2/3 of baryons at mid-rapidity are produced via baryon-antibaryon pair production, and roughly 1/3 of baryons come from the colliding nuclei.

A large variety of particle ratios have been measured, and from these ratios the chemical freeze-out parameters can be extracted. Chemical freeze-out occurs when flavor changing inelastic collisions cease. At this point the yields of various particles are fixed, and subsequent elastic scattering will not change the particle composition. Since the cross-sections for inelastic collisions are larger than the cross-sections for elastic collisions, one expects the chemical ratios to be fixed at a time before kinetic freeze-out. Various authors have performed chemical fits to the preliminary RHIC particle ratios, yielding a chemical freeze-out temperature and baryon chemical potential of $T_{ch} \approx 175$ MeV and $\mu_b \approx 40 - 50$ MeV [4].

3 Particle spectra and kinetic freeze-out

Both STAR and Phenix have measured the differential yields for various hadrons. The differential yields can be used to extract the state of the system at kinetic freeze-out. In a hydrodynamical picture particles are created with a common flow velocity and random thermal velocity. Heavier particles tend to have harder spectra, as the common flow velocity dominates over the random ther-

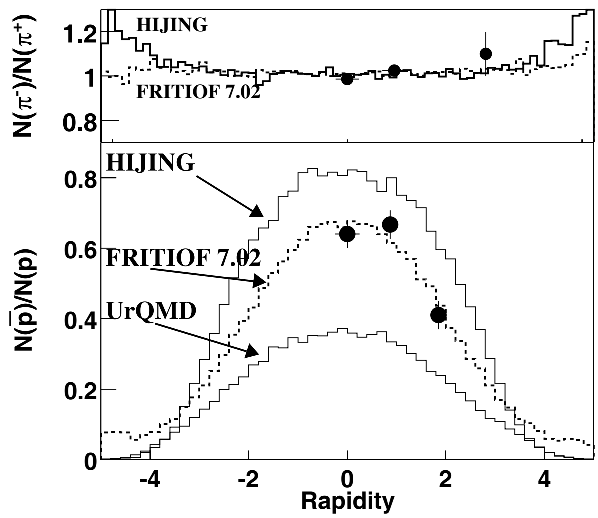

Figure 1: $\bar{p}/p$ ratio as measured by Brahms [3].

mal velocity. In Figure 2, the inverse slope parameter T,

$$\frac{dN}{m_T dm_t} \propto e^{(-m_T/T)}, \qquad (1)$$

is plotted as a function of the particle mass for preliminary STAR data [5]. The inverse slope parameter increases nearly linearly with particle mass, except for the strange hyperons. The linear increase with particle mass is an indication of transverse flow. The strange hyperons are thought to deviate from this trend due to their reduced elastic cross-sections. This suggests that the strange hyperons undergo kinetic freeze-out earlier than other non-strange particles.

Phenix has measured the mean transverse momentum of pions, kaons, and protons as a function of collisions centrality [6]. The mean transverse momentum increases with increasing centrality. This indicates larger radial flow as collisions centrality increases.

Both STAR and Phenix have fit the differential yields using a variation of the popular blast wave parameterization [7]. Both experiments extract a mean transverse flow velocity $< \beta_r > \approx 0.50 - 0.55c$ and a kinetic freeze-out temperature $T \approx 130$ MeV [4]. These freeze-out conditions are very similar to those at the SPS.

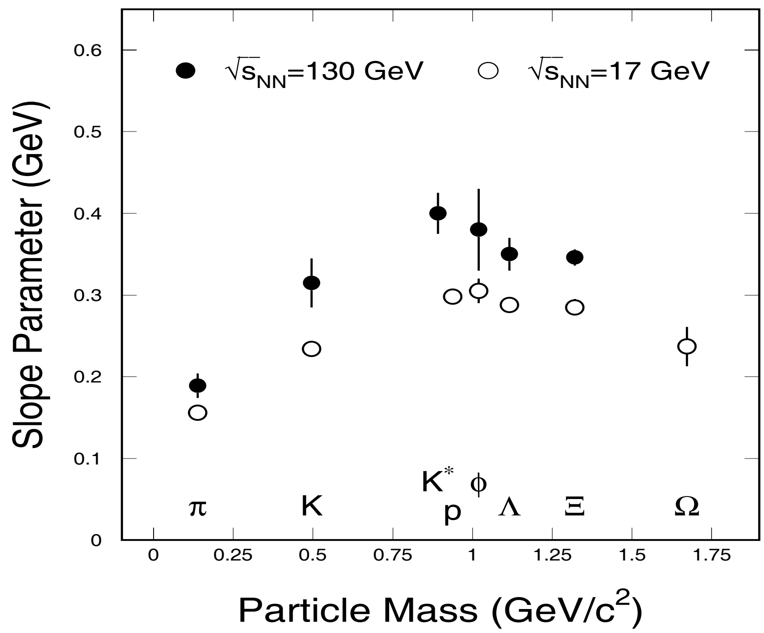

Figure 2: Slope parameters versus particle mass for SPS and STAR preliminary data.

4 Correlations

Single inclusive particle yields can give information about the momentum space configuration at kinetic freeze-out. In reality, the strongest constraints on the models come from the reconstruction of the full freeze-out configuration,

$$f_i(x,p). \tag{2}$$

f is the probability for producing a particle of type i with momentum p at position x. The single inclusive yields represent an integral over the spatial component of the freeze-out configuration,

$$E\frac{d^3N}{d^3p} = \int f_i(x,p)d^4x. \tag{3}$$

In order to understand the configuration space information and the position-momentum correlations various types of two-particle correlations are measured.

4.1 Particle Interferometry

Momentum space particle correlations are produced through the strong and electromagnetic interactions as well as through quantum statistics. The most commonly measured correlation function is for identical charged pions. As the Coulomb interaction is thought to be well understood, the data is corrected for the Coulomb interaction leaving only the correlations due to quantum statistics. An enhancement at low relative momentum Q is observed, and the width of the enhancement is inversely related to the size of the emitting source.

Both STAR and Phenix have measured the transverse momentum dependence of the $\pi^+\pi^+$ and $\pi^-\pi^-$ interferometry radii. The radii are measured in the out-side-long system, where Q_{long} is the momentum difference along the beam direction, Q_{out} is the momentum difference transverse to the beam direction and parallel to the total transverse momentum of the pair, and Q_{side} is orthogonal to Q_{out} and Q_{long}. In this frame, R_{side} is closely related to the (p_T dependent) transverse size of system, while R_{out} measures both the transverse size and the duration of particle emission. It is expected that a system that undergoes a phase transition with a large latent heat will stall and emit pions over a long duration [8]. This will lead to a large R_{out}/R_{side} ratio.

Figure 3 shows the k_T (average p_T of the pair) dependence of the HBT radii for central collisions at AGS, SPS and RHIC energies [9]. The transverse radii, R_{out} and R_{side}, do not show any energy dependence and do depend on p_T at all energies. At low p_T, the transverse HBT radii are around 6 fm. This should be compared to the initial nuclear size of around 3 fm (the equivalent Gaussian radius of a Au nucleus). Between collision and final freeze-out there is a factor of two expansion in the transverse plane. In addition, we see that outward and side-ward radius parameters are similar at all energies and transverse momenta, suggesting a sudden freeze-out of the pions. There is no apparent long-lived mixed phased as predicted by models including a large latent heat and consequent stall of the system. These data suggest a system with either large opacity, or strong radial flow induced position-momentum correlations that cause an apparent short duration of particle emission.

The R_{long} radius parameter increases with increasing $\sqrt{s}$. In a hydrodynamical picture, the longitudinal radius parameters at mid-rapidity follow the Sinyukov relation [10],

$$R_{long} = \sqrt{\frac{2T}{m_T}}\tau, \tag{4}$$

where T is the kinetic freeze-out temperature and τ is mean time of particle emission. The single particle spectra suggest a similar kinetic freeze-out temperature at AGS, SPS, and RHIC energies. An increasing R_{long} and similar kinetic freeze-out temperature suggests that the system freezes out later in higher energy nucleus-nucleus collisions.

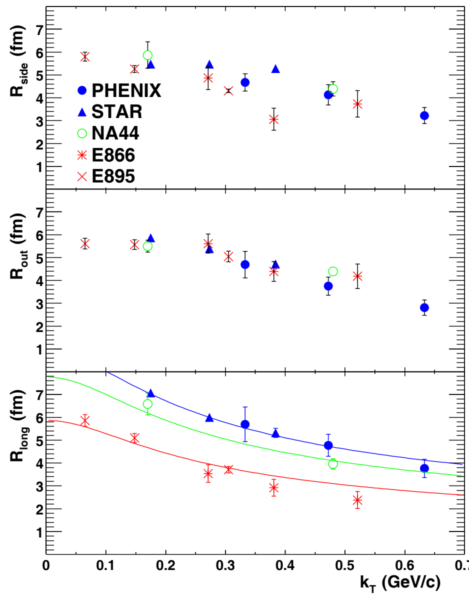

Figure 3: k_T dependence of HBT radii [9]

The STAR HBT data have been fitted using a blast wave model similar to that used to fix the single particle inclusive spectra. This model includes explicit position momentum correlations times, and takes into account the duration of particle emission ($\Delta\tau$), the cylinder transverse radius R, the kinetic freeze-out temperature T, and the mean radial flow velocity $\langle\beta_r\rangle$. The STAR HBT data can be fit with $R = 13.5$ fm, $T = 110$ MeV, $\langle\beta_r\rangle = 0.52c$, and $\Delta\tau = 1.5$ fm. The kinetic freeze-out temperature and radial flow velocity are similar to those suggested by fits to the single inclusives. The transverse radius indicates a factor of two expansion from the initial nuclear size. The freeze-out duration is constrained to be very short. A longer freeze-out duration would cause the R_{out}/R_{side} ratio to increase with p_T, which is inconsistent with both STAR and Phenix data.

4.2 Anisotropic flow

Angular correlations among particles are often characterized in terms of the Fourier components of the particle distributions relative the reaction plane. At RHIC, the only large Fourier component is the second order $(cos(2\phi))$ component commonly referred to as elliptic flow. The measurement of elliptic flow (v_2) can also be used to examine the freeze-out configuration in momentum and position space. STAR has measured the transverse momentum dependence of v_2 for pions, kaons, and protons [11]. These data can be fit in the blast wave formalism including both momentum space and spatial anisotropies, yielding a kinetic freeze-out temperature of 100 ± 24 MeV and a mean radial flow velocity of 0.54 ± 0.03 MeV. The data also favor a source with both momentum space and coordinate space anisotropies.

4.3 Nuclear Coalescence

Nuclear cluster formation is thought to occur at RHIC via the coalescence of nucleons during the final stages of kinetic freeze-out. Thus, the measurements of nuclear clusters probe the spatio-temporal correlations among nucleons in the same way that HBT probes these correlations for pions. STAR has measured the yields of the light antinuclei $\bar{p}$, $\bar{d}$, and $^3\overline{He}$ [12]. These yields have been analyzed in a coalescence framework [13] to extract the homogeneity volume for antinucleons. These homogeneity volumes can be directly related to the homogeneity volumes $(R_\perp^2 R_L)$ extracted from HBT, and this comparison is shown in Figure 4. The homogeneity volumes decrease monotonically with transverse mass. In addition, the antinucleus data and pion interferometry data seem to follow a common mass systematic. This indicates that antinucleons and pions freeze-out simultaneously.

The antinucleus data can also be used to extract the *chemical* parameters of the system at *kinetic* freeze-out. A statistical coalescence model is used, with the freeze-out temperature and baryon chemical potential as free parameters. Fitting the antinucleus data give $T \approx 130$ MeV and $\mu_b \approx 30$ MeV. As shown earlier, a similar model applied to the ratios of light meson and baryon ratios yields $T_{ch} \approx 175$ MeV and $\mu_b \approx 40 - 50$ MeV. This indicates that the system cools between chemical and kinetic freeze-out. In addition, the freeze-out temperature extracted from the antinucleus yields is similar to the kinetic freeze-out temperature extracted for the single inclusive particle spectra, HBT, and the anisotropic flow. All measurements sensitive to the temperature at kinetic freeze-out agree in the range $T = 100 - 130$ MeV.

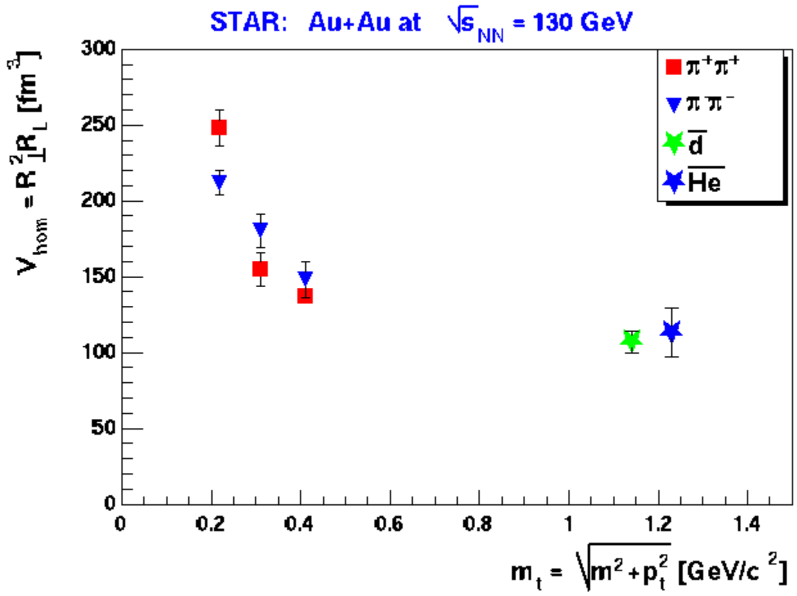

Figure 4: Transverse mass dependence of the homogeneity volumes extracted from pion interferometry and antinucleus coalescence.

5 Can we exclude a single freeze-out model?

Recent work, presented at this conference, shows that the shape of the particle p_T spectra and the absolute yields of various hadron species can be accounted for assuming a single freeze-out hyper-surface with no re-interactions after chemical freeze-out [14]. This is in contradiction to the common assumption of two stage chemical and kinetic freeze-out. In the single freeze-out model, the lower apparent temperature at "kinetic" freeze-out is due to the cooling of the particle spectra due to resonance decays. This interpretation can not be ruled out using only the single particle inclusive data.

In order to critically asses this model, measures sensitive to the six-dimensional phase-space density of the produced particles must be used. The unnormalized p_T spectrum for a particle species can be calculated from the common thermodynamic parameters (T and μ_b). In order to get the particle yield correct, one must simply adjust the volume V over which the particles are produced. In order to check whether this volume V is the correct choice, the predictions of the model can be compared to correlation data.

The cylindrically symmetric source used in the single freeze-out model is very similar to the blast wave parameterization used to fit the STAR HBT data. In the single freeze-out model, however, the radius of the cylinder is 6.69 fm, whereas the cylinder radius extract from the HBT data is of order 13.5 fm. This would indicate a factor of two discrepancy in the source size predicted by the single freeze-out model compared to the available data. A final conclusion on the validity of the single freeze-out model, however, cannot be made until the effects of resonance decays and excluded volume corrections on the predicted HBT radii are carefully considered within the context of the single freeze-out model.

6 Conclusions

At RHIC, a system with low net-baryon density at mid-rapidity is produced. 2/3 of the baryons come from baryon-antibaryon pair production, while 1/3 of mid-rapidity net baryons come from the initial nuclei. The system undergoes chemical freeze-out at $T_{ch} \approx 175$ MeV and $\mu_b \approx 40 - 50$ MeV. The single particle p_T spectra, as well as the HBT, elliptic flow, and antinucleus measurements, suggest that the system undergoes further elastic re-scattering until final freeze-out at $< \beta_r > \approx 0.50 - 0.55c$ and a kinetic freeze-out temperature $T \approx 130$ MeV.

The correlation data indicate that the system expands by roughly a factor of two in the transverse direction before freeze-out. The energy dependence of the R_{long} radius parameter indicates that system lives longer at RHIC compared to lower energies. At all energies $R_{out}/R_{side} \approx 1$, suggesting a short duration of pion emission. The antinucleus data, analyzed in a coalescence model, indicate a common systematic with the pion interferometry data. This suggests that pions and antinucleons freeze-out at similar times.

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